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APPLICATION OF A BIP CONSTRAINED OPTIMIZATION MODEL COMBINED WITH NASA's ATLAS MODEL TO OPTIMIZE THE SOCIETAL BENEFITS OF THE USA's INTERNATIONAL SPACE EXPLORATION AND UTILIZATION INITIATIVE OF 1/14/04.

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ABSTRACT

The 1/14/04 USA Space Exploration/Utilization Initiative[1] invites all Space-faring Nations, all Space User Groups in Science, Space Entrepreneuring, Advocates of Robotic and Human Space Exploration, Space Tourism and Colonization Promoters, etc., to join an International Space Partnership. **With more Space-faring Nations and Space User Groups each year, such a Partnership would require Multi-year (35 yr.-45 yr.) Space Mission Planning. With each Nation and Space User Group demanding "priority" for its missions, one needs a methodology for objectively selecting the "best" mission sequences to be added annually to this 45 yr. Moving Space Mission Plan. How can this be done?** Planners have suggested building a **Reusable, Sustainable, Space Transportation Infrastructure (RSSTI)** to increase Mission synergism, reduce cost, and increase scientific and societal returns from this Space Initiative. **Morgenthaler and Woodcock presented a Paper at the 55th IAC, Vancouver B.C., Canada, entitled "Constrained Optimization Models For Optimizing Multi - Year Space Programs."[2]** - This Paper showed that a Binary Integer Programming (BIP) Constrained Optimization Model combined with the NASA ATLAS Cost and Space System Operational Parameter Estimating Model[3] has the theoretical capability to solve such problems. **IAA Commission III, Space Technology and Space System Development, in its ACADEMY DAY meeting at Vancouver, requested that the Authors and NASA experts find several Space Exploration Architectures (SEAs), apply the combined BIP/ATLAS Models, and report the results at the 56th Fukuoka IAC. While the mathematical Model is in Ref. [2], this Paper presents the Application saga of that effort.**

1.0 BIP CONSTRAINED OPTIMIZATION

This BIP Example, as found in the Hillier and Lieberman, Operations Research Textbook, 8th Edition[4], is a classic for explaining the BIP Constrained Optimization Model (plus NASA's ATLAS Cost and Operational Parameter Estimating Model[3]) when applied to such Optimization problems. The California Co. is building new factories in either Los Angeles or San Francisco, or both, and is also considering building at most one new warehouse, but it will restrict any new warehouse to a city where a new factory is being built. Net present value (total profitability, taking into account the time value of money) is used in Table 1. Alternative Net Present Value and Capital Cost are listed in millions of $.

To Build? "yes"=1, "no"=0.	Binary Decision Variable	Net Pres. Value	Capital Req'd
Binary X_i	X_i	($'s in millions)	
1. Factory in L.A.?	X_1	$9	$6
2. Factory in S.F.?	X_2	$5	$3
3. Warehouse in L.A.?	X_3	$6	$5
4. Warehouse in S.F.?	X_4	$4	$2
Capital Available:	$10 million		

Table 1: Decision Data for the California Co.

The California Co. BIP Constrained Optimization Problem has 4 binary variables: Xi, "yes"=1, "no" = 0, i=1,2,3,4. Let Z = the total net present value of these decisions, i.e., the **Pay-off Function.** Then,

$Z = 9X_1 + 5X_2 + 6X_3 + 4X_4,$ (1)

where the coefficients are in million $ units.

With the coefficients in million $ units, **the Capital expenditure constraint** is

$6X_1+3X_2+5X_3+2X_4 \leq 10.$ (2)

In Table 1, decisions 3 and 4 are contingent upon 1 and 2. The last two decisions represent mutually exclusive constraints. **We need the constraint**:

$X_3 + X_4 \leq 1$. (At most 1 new warehouse.) (3)

Decisions 3 and 4 are decisions contingent on decisions 1 and 2, respectively, because **the company would consider building a warehouse in a city only if a new factory were going to be there also.** Thus one constraint is that $X_3 = 0$ if $X_1 = 0$. Similarly, $X_4 = 0$ if $X_2 = 0$. We can therefore write the constraints as:

$X_3 \leq X_1$, and $X_4 \leq X_2$. (4)

The complete BIP Model is thus:
Maximize $Z = 9X_1 + 5X_2 + 6X_3 + 4X_4$,
Subject to:

$$\begin{array}{rrrrl} 6X_1 + & 3X_2 + & 5X_3 + & 2X_4 & \leq 10, \\ & & X_3 + & X_4 & \leq 1, \\ -X_1 & & + X_3 & & \leq 0, \\ & -X_2 & & + X_4 & \leq 0, \end{array} \qquad (5)$$

and X_i is binary for i = 1,2,3,4. Such BIP problems are readily solved by the BIP Branch-and-Cut algorithmic approach. (See [4] p. 521)

In this simplified Example, however, there are only $2^4 = 16$ possible 'four-tuples' $\{(X_1, X_2, X_3, X_4)\}$, such as (1, 0, 1, 0), (1, 1, 0, 1), etc., to test. It is easy to enumerate all of the 16 possible solutions, eliminate any that fail one or more of the constraints, plug the remaining "feasible" solutions (i.e., those satisfying <u>all</u> of the constraints) into the Z payoff function and **choose the feasible solution or solutions that maximize Z. In this case, the maximizing 'four-tuple' is X*= (1,1,0,0) and the maximized Z=Z*= 14.**

But, what can be done when one is faced with a BIP Constrained Optimization Problem in which there are, say, 20 variables and, say, 35 constraints? Since $2^{20} = (2^4)^5 = (16)^5 = 1{,}048{,}576$, the idea of testing all possible solutions manually to find the feasible ones, and then to find the feasible solution or solutions which maximize Z, is not practical, considering that there are $>10^6$ 'twenty-tuples', $\{(X_1, X_2, X_3, \text{---------} X_{20})\}$, to test.

The good news is that research in recent years has produced a number of **Solvers,** such as **CPLEX 6.5**, which is reported to have successfully used a sophisticated Branch-and-Cut algorithm to solve a real-world problem with over 4,000 functional constraints and over 120,000 variables!!! (H & L, 7th Ed.) [4] Thus, **Solvers** are available to handle very large BIP Constrained Optimization Problems, such as would arise when this methodology is applied to the hundreds of missions and thousands of constraints involved in optimizing a realistic SEA.

2.0 BIP/ATLAS[3] SEA OPTIMIZING MODEL

2.1 The Purpose of ATLAS [3]

ATLAS stands for the **Advanced Technology Lifecycle Analysis System**. The ATLAS system provides the capability for a single user to create a SEA from a Space Mission Vehicle model library, configure the vehicles by entering performance parameters and selecting technologies, and generating charts for system masses, costs, and architecture economics. With the capability to configure multiple systems within an architecture, the user can see the impact of various performance and technology decisions. As the user selects technologies for each system, an Integrated Technology Analysis Method (ITAM) module builds a portfolio and generates an Integrated Technology Index (ITI), a composite value calculated from: Technology Readiness Levels (TRL); Technology Need Values (TNV); and Research and Development Degree of Difficulty (RD^3). A cost model derived from the NASA Air Force Cost Model (NAFCOM) includes Cost Estimating Relationships (CERs) and historical programmatic data for generating costs from mass statements generated by selected System Models. An Economics model uses time lines specified in a Campaign Profile to distribute the SEA development and deployment costs over several years.

2.2 The ATLAS Modeling Approach.

A Collaborative Engineering Environment (CEE) brings together experts from a variety of disciplines, where each team member has a discipline oriented analysis tool that is integrated through a central database or spreadsheet. During a CEE session, the team analyzes a conceptual design and generates inputs for a cost and economics model. This approach provides flexibility to explore a variety of configurations and a detailed analysis through powerful discipline -oriented tools. Costs for a CEE session can be expensive due to the number of people involved, computing resources, and the effort required to integrate disparate tools.

The ATLAS modeling approach integrates Microsoft Excel based system-oriented models with standardized interfaces to a common cost and economics model. A single user can assemble a SEA by selecting various system models, entering performance parameters and selecting technologies. This approach requires system model developers or teams of developers to determine the performance and technology parameters that drive the mass of the system. Essentially, the ATLAS model library becomes a knowledge base because the system model captures the complex Mass Estimating Relationships (MERs) that apply technology performance metrics. System models may include multidisciplinary MERs derived from historical data, physics equations derived from analyzing a system concept, or look-up tables generated from discipline-oriented design and analysis tools.

Multi-Year SEAs of 160-200+ Missions are common. We must have a **Pay-off Function, Z,** which is to be maximized. In the Vancouver Paper[2] a Committee of Senior, high-integrity "Scientists, Entrepreneurs, Explorers, etc., and Astronautical experts" was to be formed representing all the User Groups, the Space-faring Nations, and all other Investors in the 1/14/04 Partnership. These experts would accept all plausible Missions and would assign to each successful mission the Committee's calculated "average worth" or "average value" on a scale of 1 to 100. Then, introducing the probability formulae for the 'probability of mission success' of the various vehicle stages and the 'probability of success' for the multiple rendezvous and dockings of those missions that will land and take-off again from Planetary surfaces, **Z can be defined as the sum of the expected values, i.e., the sum of (the probability of mission success times the " average value" of the mission) for each of the missions being considered in the 30yr.- 45yr. Mission Planning Cycle or SEA.** If there were 200 missions, then there would be $\geq 2^{200}$ binary variables! In addition, there would be many constraints between certain missions and the heavy traffic at the "Gateways", such as the Earth/Moon System L_1 point or the Sun/Earth System L_2 point and the various missions waiting in line to use these Gateways, or to pick-up consumable supplies deposited for them by earlier supply missions, etc. In fact, the number of constraints will thus also be very large.

There are many constraints of a funding nature. **If the Partnership's Budget in the i^{th} year is B_i** and the number of missions are indeed ~200, then we know that some of the missions will not have vehicle fabrication funds expended until, say, the year 2030+. But, the fact is that they will be in design before they are being manufactured, so that design costs occur. Hence **the sum of all of the expenditures of all of the missions in the total SEA for the i^{th} year must be $\leq B_i$, for each i.** Also, the total of the expenditures of all of the missions over all of the years must be less than the Partnership's Master Budget for the total planning cycle. There will be other types of constraints, some imposed by International Space Law, e.g., restrictions on nuclear propulsion; some (in the early Planning years) because specifically needed technology is not yet ready and so the missions requiring the technology must be dropped or delayed. If some User Group's repeatable Missions, say, delivering cargoes to and from the Moon, require prototype development of a new vehicle and the Users do not invest to qualify that prototype development, then that mission and its successor repeat missions cannot fly until their R and D is completed. There could also be a limitation on the number of qualified Astronauts available in certain years. Thus the number of constraints could indeed be in the thousands. It is important for safety and efficiency's sake that planning be done on a 30 to 45 year cycle, with the cycle being moved forward by one year, each year. This allows a new vehicle, say like the Crew Excursion Vehicle (CEV), to be designed for easy modification and growth in a decade or so, etc., if the needs change. Thus the formulation of the 1/14/04 Space Initiative Optimization Problem is to select the 'best' sequence and/or sequences of Space Missions from the ~ 2^{200} '200-tuple' Missions, i.e.,$\{(x_1,x_2, \dots x_{200})\}$, that will maximize Z, the sum of the expected 'average' values of the ~ 2^{200} '2-tuples' for any typical proposed SEA. Since we have the BIP Constrained Optimization Model Tool, we can apply it to various SEAs, optimize them, and either select the 'best' one or be led to new SEAs which embody the 'best' Missions and 'best' vehicles of the SEAs that we examined. Ref.[2] contains the BIP Model. How has the NASA Contract Team plus the WAESO/MEP Team applied this methodology?

3.0 APPLYING THE MODELS TO 3 SEAs.

The CU NASA Contract Research Team, of [G. Morgenthaler P.I., G. Woodcock, F. Glover and M. Laguna] plus the 4 NSF sponsored WAESO/ MEP CU students [Vedran Alagic, Karla Alves, Kelly Kaveny, and Joe McCabe] early-on selected 3 SEAs. **These were: a) A NASA-like SEA based upon the ~ 200+ missions and the Budget that NASA[5] released in late Spring of 2005** and which was to begin in 2006 to plan Missions forward about 30-45 years into the future; **b) An SEA based upon the mission philosophy and methodology presented in the Vancouver Paper #IAC-04-IAA.3.6.1.01[6] by Ernesto Vallerani and John Mankins;** and **c) The Space Planning Methodology and "Stepping Stones To Mars" emphases of the Vancouver Plenary Session Presentation[7] by Wes Huntress, R. Farquhar, B. Foing, et al.** It was our intent under the NASA Contract that we define the most detailed sets of missions for these 3 SEAs as possible, identify the newest Space vehicles from the latest Space Industry Literature and, by examining the Space Budgets of the Space Nations and User Groups, to estimate what its such a Space Initiative Partnership might have as Annual SEA Budget. For this Cost and performance estimation area we had access to the NASA ATLAS Model Ref.[3]. These SEAs were chosen because they were available and representative, not because they are "politically" or technically tauted as 'best'. We are demonstrating BIP as a SEA optimization tool, not emphasizing any of the 3 SEAs at this time.

4.0 USE OF A STUDENT "β-TEST"TEAM TO 'PILOT' THE OPTIMIZATION OF SEAs .

The 4 NSF-funded WAESO/MEP students had studied the Constrained Optimization Example in **1.0** above and equipped themselves to apply it to Space Mission Planning. This motivated the approach of using the 4 students as a ß-Test Team and seeking 5 Semesters of Grants from WAESO/ MEP: Summer and Fall, 2004; and Spring, Summer, and Fall, 2005. This enhanced the project resource pool to utilize the student contributions at a level commensurate with Graduate School research. The students actually did Research of the type expected in Graduate School, i.e., have small pilot 'RUNs' and likely experience some failures. With this in mind, the students first tried the NASA SEA, comprising ~ 160 Missions and using the LINGO Solver from the Hillier and Lieberman Text-Book[4], 8th Edition. This used the BIP "Branch-and-Cut" Algorithm. **However, the LINGO Solver did not work!** After further experimentation, student Joe McCabe discovered that the Text-Book model was contained in a Text-book CD that had to have all of the Algorithms for the 20 Chapters of the Book. Thus each Chapter had Algorithm Solvers of only limited size and LINGO was not capable of handling problems of the size studied in our Project. **Accordingly, to create a test case that could demonstrate the soundness and viability of the basic model concept, the NASA Mission ß-test list was trimmed from 160+ to 30 Missions (and their constraints), whereupon the LINGO Solver worked!** The students were relieved and delighted. The 30 Mission SEA was not realistic, but the Student ß-Test 'RUN' * indicated that, with a realistic SEA of, say, 200 Missions and using a powerful Solver, a BIP Constrained Optimization plus ATLAS Model combination might use the "Branch-and-Cut" Algorithm to optimize SEAs of a size used in the

* Made a 'RUN' shall always mean that a Solver calculated the constrained BIP optimization of the SEA then being explored.

1/14/04 USA Space Initiative. Another challenge was embodied in the fact that the **'Output'** of a large SEA Optimization 'RUN' is just a list of those Missions that were accepted in certain years and those that were rejected, due to their failure to meet one or more constraints, or because their contribution to the overall Pay-off function, Z, was not among the most cost-effective Missions. How does one visualize these outcomes other than by such a listing? The student ß-Test Team began searching for software to convert a 2-D plot, which records the number of Mission transits over key nodal points of the 2-D plot, into a 3-D plot so **that the analyst can easily see where the traffic is most dense and is thus helped to make more rapid, valid conclusions as to the "Best" SEAs, "Best" Missions, and the "Best" Gateways.**

5.0 MATLAB HAS 2-D TO 3-D CAPABILITY.

Dr. Donald Mackison[8], CU Aerospace Eng. Sciences Dept., has expert knowledge of Matlab's extensive plotting capability, which can be used to illuminate relationships between variables. For example, the relative "cost" of paths in Space navigation, i.e., the relative number of times that a mission trajectory crosses an SEA node or orbital link in a 2-D plot of Mission Traffic of a Multi-Mission SEA can be depicted as a 3-D plot in Space if we keep count at each node and trajectory link of the number of times the 2-D node or trajectory link is used by the SEA's Missions. Given parameter arrays X ,Y, and cost variable Z, the function surf can be used to displace this data as a 3-D plot. For example, the function $z = xe^{-x^2-y^2}$ can be represented by the following code, using the functions **meshgrid** and **surf**:

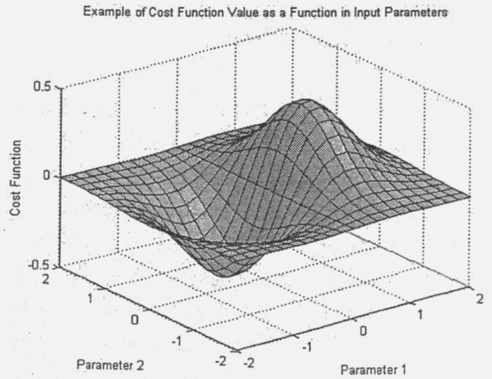

Figure 1: Example of "Cost Function" Value as a Function in Input Parameters.

Other new challenges occurred, for example, "When preparing a BIP Model 'RUN' with the myriad of inputs, how do you know that some of the missions such as a trip from the Sun/Earth L_2 point to the Earth/ Moon L_1 point, in order to take humans to Mars, is feasible? Student Alagic, used the Satellite Tool Kit (**STK**), and discovered a more sophisticated tool from JPL, the **LTool**, which helps envision difficult orbital Missions through Lagrange points.**(See Figures 2 and 3.)**

6.0 INTEGRATING STUDENT "ß-TESTS" WITH THE NASA CONTRACT EFFORTS.

The Student Team and the P.I. provided written Final Reports on the WAESO/MEP NSF Grants for each Semester. These Semester Final Reports were also sent to the Professional Experts of the NASA Contract Team: Dr. Gordon Woodcock; Profs. Fred Glover and Manuel Laguna; and the NASA COTR at NASA /MSFC, Dan O'Neil, with the request that they review the Reports, make comments, raise questions and provide specific data and suggestions to improve the application of the BIP/ATLAS Models to the Optimization of the proposed SEAs. This resulted in many excellent contributions that were shared among the entire Team. For example: Prof. Glover created a write-up and made available his BIP publication[9] about the best way to incorporate verbalized constraints into a BIP problem, and their specific algebraic simplifications , while Prof. Laguna gave a tutorial to the students that improved their ß-Test Model and will be directly applicable to the NASA Contract. While the ATLAS Model is mainly focused on the next generation of Lunar Missions, Dr. Woodcock examined the Log of Missions for the NASA 2006 SEA and increased his familiarity with ATLAS model so that he could synthesize the Cost and parameters of a new vehicle needing several stages in flight and/or a Mission that requires several operational phases for completion, such as safe orbital rendezvous after a planetary landing. A Student tutorial was given. **Table 2** shows a few lines of a **Mission Log** for the NASA SEA, which had ~200 Missions, hence there were ~200 $\{X_i\}$ binary variables. COTR Dan O'Neil supplied valuable information and Project access to ATLAS. Finally, the two Teams felt it was time to input the Vallerani/Mankins SEA to **CPLEX** and 'RUN' it.

Figure 2: STK Display of a Lunar Mission Trajectory

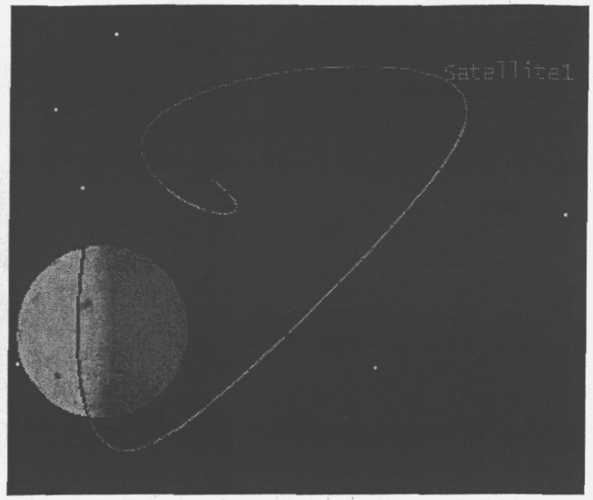

Figure 3: Second STK View of a Lunar Mission Trajectory

Mission Number	Mission Name	Description
X_1	Mars Science Lab	Mars Science Lab (MSL) is a NASA rover scheduled to launch in 2009 to perform a precision landing on Mars in 2010. EELV-M will be used to launch it in 2009. The cost of the mission is $748 Million, evenly spread over 4 years ($187 M each year).
X_2	Mars Sample Return R&D	This is the R&D of a Mars Sample Return mission. R&D cost of $600 Million includes the orbiter, lander, Earth-return vehicle. R&D is $150 M annually, starting in 2008, and ending in 2011 (4 years).
X_3	Mars Sample Return #1	This is the first sample return. $187 Million cost in 2012 includes EELV-H and the vehicle.
X_4	Mars Sample Return #2	This is the second sample return. $187 Million cost in 2012 includes EELV-H and the vehicle.
X_5	Mars Sample Return #3	This is the third sample return. $187 Million cost in 2013 includes EELV-H and the vehicle.

Table 2: The First 5 Missions of the NASA 2006 SEA[5]: an Example of a "Mission Log"

7.0 THE VALLERANI/MANKINS SEA CPLEX 'RUN'

Prof. Laguna created a software package consisting of the CPLEX software using the Vallerani/Mankins SEA data (194 missions) and the ATLAS cost and parameter input software. Data was assembled by: the Students, Dr. Woodcock, and the P.I., and put into a Mission Log by Vedran Alagic. BIP Model enhancements were introduced by Profs. Glover and Laguna, consisting of changing the model to incorporate the many constraints to choose between the many Missions, and they identified additional model enhancements as a foundation for examining more advanced algebraic forms of the problem. The Vallerani/Mankins SEA was now of the correct size, but many vehicles and Missions were still lacking specific details. But, the 'RUN' would indicate whether the CPLEX Solver could do the job, i.e., optimize the SEA. To the great joy of all, it worked, and gave realistic and interpretable outcomes! Both pages 7 and 8 show the Vallerani/ Mankins SEA 'RUN' results.

8.0 Optimizing the Vallerani/Mankins SEA

Maximize $Z = \sum_{i=1}^{N} (AverageValue_i)(X_i)$

considering all $\{(X_1, X_2, \ldots X_N)\}$, i.e., 2^N Binary N-tuples, subject to the Constraints given below, and with N = 194 Missions.

Maximize the Pay-off/Objective Function, Z=:

obj: 78.4 X1 + 78.4 X2 + 78.4 X3 + 78.4 X4 + 78.4 X5 + 78.4 X6 + 78.4 X7 + 78.4 X8 + 78.4 X9 + 78.4 X10 + 78.4 X11 + 78.4 X12 + 78.4 X13 + 78.4 X14 + 78.4 X15 + 78.4 X16 + 78.4 X17 + 78.4 X18 + 78.4 X19 + 78.4 X20 + 78.4 X21 + 78.4 X22 + 78.4 X23 + 78.4 X24 + 78.4 X25 + 78.4 X26 + 78.4 X27 + 78.4 X28 + 78.4 X29 + 78.4 X30 + 78.4 X31 + 78.4 X32 + 78.4 X33 + 78.4 X34 + 78.4 X35 + 78.4 X36 + 78.4 X37 + 78.4 X38 + 78.4 X39 + 78.4 X40 + 78.4 X41 + 78.4 X42 + 78.4 X43 + 78.4 X44 + 78.4 X45 + 78.4 X46 + 78.4 X47 + 78.4 X48 + 78.4 X49 + 78.4 X50 + 78.4 X51 + 78.4 X52 + 78.4 X53 + 78.4 X54 + 78.4 X55 + 78.4 X56 + 78.4 X57 + 78.4 X58 + 78.4 X59 + 78.4 X60 + 78.4 X61 + 78.4 X62 + 78.4 X63 + 78.4 X64 + 78.4 X65 + 78.4 X66 + 78.4 X67 + 78.4 X68 + 78.4 X69 + 78.4 X70 + 78.4 X71 + 78.4 X72 + 78.4 X73 + 78.4 X74 + 78.4 X75 + 78.4 X76 + 78.4 X77 + 78.4 X78 + 78.4 X79 + 78.4 X80 + 78.4 X81 + 78.4 X82 + 78.4 X83 + 78.4 X84 + 78.4 X85 + 78.4 X86 + 78.4 X87 + 78.4 X88 + 78.4 X89 + 78.4 X90 + 78.4 X91 + 78.4 X92 + 78.4 X93 + 78.4 X94 + 78.4 X95 + 78.4 X96 + 78.4 X97 + 78.4 X98 + 78.4 X99 + 78.4 X100 + 78.4 X101 + 78.4 X102 + 92.15 X103 + 92.15 X104 + 92.15 X105 + 92.15 X106 + 92.15 X107 + 92.15 X108 + 92.15 X109 + 92.15 X110 + 92.15 X111 + 92.15 X112 + 92.15 X113 + 92.15 X114 + 92.15 X115 + 92.15 X116 + 92.15 X117 + 92.15 X118 + 92.15 X119 + 92.15 X120 + 92.15 X121 + 92.15 X122 + 92.15 X123 + 92.15 X124 + 92.15 X125 + 85.5 X126 + 85.5 X127 + 85.5 X128 + 85.5 X129 + 85.5 X130 + 85.5 X131 + 85.5 X132 + 85.5 X133 + 85.5 X134 + 86.4 X135 + 86.4 X136 + 86.4 X137 + 86.4 X138 + 86.4 X139 + 86.4 X140 + 86.4 X141 + 86.4 X142 + 86.4 X143 + 86.4 X144 + 86.4 X145 + 86.4 X146 + 86.4 X147 + 86.4 X148 + 86.4 X149 + 86.4 X150 + 86.4 X151 + 86.4 X152 + 86.4 X153 + 86.4 X154 + 86.4 X155 + 86.4 X156 + 86.4 X157 + 86.4 X158 + 86.4 X159 + 86.4 X160 + 86.4 X170 + 86.4 X171 + 86.4 X172 + 86.4 X173 + 86.4 X174 + 86.4 X175 + 86.4 X176 + 86.4 X177 + 86.4 X178 + 86.4 X179 + 86.4 X180 + 86.4 X181 + 86.4 X182 + 86.4 X183 + 86.4 X184 + 86.4 X185 + 86.4 X186 + 86.4 X187 + 86.4 X188 + 86.4 X189 + 86.4 X190 + 86.4 X191 + 86.4 X192 + 86.4 X193 + 86.4 X194

8.1 Optimize, Subject to the Constraints:

a) Missions depending on other missions:

c1: X2 - X1 <= 0
c2: X3 - X1 <= 0
c3: X4 - X1 <= 0
c4: X5 - X1 <= 0
c5: X6 - X1 <= 0
c6: X7 - X1 <= 0
c7: X8 - X1 <= 0
c8: X9 - X1 <= 0
c9: X10 - X1 <= 0
c10: X11 - X1 <= 0

Both missions X = 0 ≡ "not go". Both missions X = 1 ≡ "go"; i.e., = 1 and 1 goes; 0, 1 does not go.

b) Try "Blocks of Missions", e.g., going to the Moon, say i=1-39, vs. going to Mars, i=40-198.

$Z = Y\left(\sum_{i=1}^{39} X_i\right) + (1-Y)\sum_{i=40}^{198} X_i$, Y = "0", or "1".

$$Z = Y\left(\sum_{i=1}^{39} X_i\right) + (1-Y)\sum_{i=40}^{198} X_i .$$

If $Y_1 = 1$, then the system chooses X1 to X39, or, if $Y_1 = 0$, it chooses X40 to X198.

Alternative Missions Constraints:

c125: X1 + X2 + X3 + X4 + X5 + X6 + X7 + X8 + X9 + X10 + X11 + X12 + X13 + X14 + X15 + X16 + X17 + X18 + X19 + X20 + X21 + X22 + X23 + X24 + X25 + X26 + X27 + X28 + X29 + X30 + X31 + X32 + X33 + X34 + X35 + X36 + X37 + X38 + X39 - 39 Y1 >= 0

NOTE: The objective function coefficients are computed using the NASA ATLAS Model and/or using probability theory to calculate mission success as appropriate when Multi-Stage Vehicles are used and/or various rendezvous and docking operations must be employed to land on a celestial body and return again to an orbital vehicle which will carry astronauts or samples back to Earth.

8.2 Result: Optimizing Vallerani/Mankins SEA

- MIP Presolve (See [4], p.522) eliminated 60 rows and 83 columns.
- MIP Presolve modified 209 coefficients.
- The Aggregator did 15 substitutions.
- The reduced MIP has 74 rows, 100 columns, and 284 non-zeros.
- Presolve time = 0.01 sec.
- Z*max = 9646.15

Values =

- X40 1.000000
- X41 1.000000
- X42 1.000000
- X43 1.000000
- X44 1.000000
- X57 1.000000
- X58 1.000000
- X59 1.000000
- X60 1.000000
- X61 1.000000
- X62 1.000000
- X63 1.000000
- X64 1.000000
- X65 1.000000
- X66 1.000000
- X67 1.000000
- X68 1.000000
- X126 1.000000
- X127 1.000000
- X129 1.000000
- X132 1.000000
- X173 1.000000
- X174 1.000000
- X175 1.000000
- X176 1.000000
- X177 1.000000
- X178 1.000000
- X179 1.000000
- X180 1.000000
- X181 1.000000
- X182 1.000000
- X183 1.000000...

All other variables in the range 1-198 are zero.

8. 3 What Has Been Learned ?

Analysis of the results provided useful information and insights. Specifically, the trial 'RUN' verified and documented the satisfactory performance of CPLEX (8.0) on BIP problems that are representative of those encountered in optimizing real world, Multi-Year Mission-Planning , such as the Vallerani/ Mankins SEA[6], as a typical Space Initiative of 1/14/04.

The NASA Contract Plan was to 'RUN' 3 SEAs, namely: the NASA 2006 SEA[5]; the Vallerani/ Mankins SEA[6], emphasizing the use of the Earth/Moon L_1 Gateway; and the Wes Huntress/ Farquhar, et al., SEA[7], exploring the use of the Sun/Earth L_2 Gateway. The student Team and Dr. Woodcock spent several iterations developing the **Mission Logs (See Table 2)** to represent the Space Exploration philosophies and importance of the recommended Missions in each SEA; and a first set of Mission Logs were produced. The Plan was to have perfected these data to the extent possible and then to make the desired NASA Contract 'RUNS', including the Plan to apply two other Solvers such as Tabu Search (or other) and Simulated Annealing (or other) to judge the relative efficiencies and uses of these Solvers in different situations.

However, based on the fact that NASA Budget uncertainties postponed the start of the Contract work from March 1, 2005, to April 20, 2005, thus removing nearly two months from the time originally available to complete the Project, and with the arrival of the Fall Semester, a "No Cost Extension of the Project Completion Date to October 31, 2005" was obtained from NASA. The following Plan was then decided upon: a) During August and early September, Dr. Woodcock, the 4 WAESO/MEP students, and the P.I. would focus on forming the best possible Mission Logs of the NASA; Vallerani/Mankins; and the Wes Huntress, et al., SEAs that could be inferred from their papers, etc.; b) Profs. Glover and Laguna would then immediately make the 3 (SEAs) x (3 Solvers) = 9 'RUNS'; and c) Profs. Glover and Laguna would also help the Project Team to interpret the 'RUN' data and to formulate the Research Contract Conclusions.

The Conclusions would include: noting the 'Best' Space strategies indicated by the results of the different SEAs; selecting the 'most efficient' of the different Mission and Vehicle designs; and the 'Best' of the different Space Operations and Gateways.

Conclusions were also sought as to which were the most efficient of the Solvers for optimizing the BIP/ATLAS Constrained Optimization SEAs. Also, what alternative Space Planning and different Problem Applications might the different Solvers have? Etc.

On 9/9/05, the P.I. was notified by WAESO/MEP of receiving the CU proposed Fall Semester, 2005, Grant for the 4 students!

8. 4 The Results of the Final 9 SEA 'RUNS'.

Dr. Gordon Woodcock and the 4 CU students developed the input data for the 3 SEAs, the CU Team's Solver Experts made the 9 SEA/ Solver case 'RUNs' and the results are listed in Table 3.

Name of Solver	**The NASA 2005 (for 2006 and beyond) SEA 'RUN'**	**The Ernesto Vallerani/ John Mankins SEA 'RUN'**	**The Wes Huntress, et al., "Stepping Stones" SEA 'RUN'**
ILOG CPLEX 8.0 (BRANCH & BOUND)	Z*max value = 21,946.80 Sol'n T ~ 0	Z*max value = 9,646.15 Sol'n T ~ 0	Z*max value = 8,382.55 Sol'n T ~ 0
OPtTEK/ OPTQUEST (i.e., TABU SEARCH AND SCATTER SEARCH)	Z*max value = 21,946.80 Sol'n T ~ 0	Z*max value = 9,646.15 Sol'n T ~ 0	Z*max value = 8,382.55 Sol'n T ~ 0
LPSolve 5.1	Suboptimal Z*max value = 20,973.00 Sol'n T ~ 0	Z*max value = 9,646.15 Sol'n T ~ 0	No solution. Sol'n T ~ 0

Table 3. Evaluation/Cost-Benefit Scores of SEAs/Solvers (T is time;)

In Section 8.2, p.8, we presented the result of a CPLEX run of the Vallerani/Mankins SEA, which had the Z*max value of 9646.15. We now discuss the TABU SEARCH (OPTQUEST) Solver results for the Vallerani/Mankins SEA. The results for the block of Missions X40-X183 were the same as for the CPLEX run and, as shown above, Z*max = 9646.15. The zero value variables ,X_i, were again the same for this Solver as for the CPLEX Solver, as shown in the array below.

X's = 1, i.e., = These Missions Are Included

X40	X81	X122
X41	X82	X123
X42	X83	X124
X43	X84	X125
X44	X85	X126
X45	X86	X127
X46	X87	X129
X47	X88	X131
X48	X89	X133
X49	X90	X139
X50	X91	X140
X51	X92	X141
X52	X93	X142
X53	X94	X143
X54	X95	X144
X55	X96	X145
X56	X97	X146
X57	X98	X148
X58	X99	X149
X59	X100	X150
X60	X101	X157
X61	X102	X159
X62	X103	X162
X63	X104	X165
X64	X105	X168
X65	X106	X171
X66	X107	X173
X67	X108	X174
X68	X109	X175
X69	X110	X176
X70	X111	X177
X71	X112	X178
X72	X113	X179
X73	X114	X180
X74	X115	X181
X75	X116	X182
X76	X117	X183
X77	X118	Y3
X78	X119	Y4
X79	X120	
X80	X121	

X's = 0, i.e., = These Missions Are Excluded		
X1	X27	X155
X2	X28	X156
X3	X29	X158
X4	X30	X160
X5	X31	X161
X6	X32	X163
X7	X33	X164
X8	X34	X166
X9	X35	X167
X10	X36	X169
X11	X37	X170
X12	X38	X172
X13	X39	X184
X14	X128	X185
X15	X130	X186
X16	X132	X187
X17	X134	X188
X18	X135	X189
X19	X136	X190
X20	X137	X191
X21	X138	X192
X22	X147	X193
X23	X151	X194
X24	X152	Y1
X25	X153	Y2
X26	X154	

As mentioned in Table 3, LPSolve (5.1), gave the same solution and objective function value = 9646.15 as CPLEX (8.0) and TABU SEARCH for Vallerani/Mankins' SEA. LPSolve found a sub-optimal solution with an objective function = 20,973.00 for the NASA SEA. It failed to solve the Wes Huntress, etal., SEA because it encountered numerical errors associated with a non-singular basis.

8. 5 Reflections on the Research Study

Table 3 shows that there are several Solvers that can be applied to the 3 Representative SEAs to optimize the Expected 'average' Value of 'Z ,' the sum of the individual expected 'average' Values of the Missions of the 3 realistic Trial-Run SEAs. As stated in Section 5.0, the 3 SEAs were not used because they are necessarily the best available, although each was quite realistic in the thinking of competent Aerospace Mission Planning experts at the time they were formulated. Rather, they are typical in size and complexity of the kind of SEA missions, vehicles, and funding levels thought appropriate in the past 3 years. The important point for this paper is that the BIP Constrained Optimization/ATLAS Model, together with modern Solvers successfully worked to optimize such typical SEAs: **1) ILOG'S CPLEX[11] (8.0)** is a commercial computer package with algorithms for solving linear, quadratic, and mixed - integer programming problems, using state-of-the-art cuts, heuristics, and a variety of branching and node selection strategies; **2) OptQuest[12]** (Tabu Search and Scatter Search) is a commercial computer package by OptTek, a general optimization solver for complex systems. In contrast to CPLEX, OptQuest does not require a mathematical formulation of the problem to be solved. A typical application of OptQuest consists of finding an optimal configuration of a system that is represented by a computer simulation; **3) LPSolve[13] (5.1)**. is a non-commercial mixed – integer programming solver based on the revised simplex method, employing the branch-and-bound optimization method.

More recent relevance of this research effort is that the new NASA Administrator, Dr. Michael Griffin, despite the new Budgetary Austerity brought on by the current financial stresses of the US military efforts and the recent Natural catastrophes of Earthquakes and Hurricanes, etc., has stated[10] that NASA is planning to continue on to fulfill the US's Presidential Initiative of 1/14/04, i.e., to go to the Moon by 2018 (2 yrs ahead of the 2020 target date) and to fund about $8 billion/yr for 13 years to achieve the original 1/14/04 Space Exploration Initiative. Probably the other main thrust of the 1/14/04 Space Initiative, i.e., to form an International Partnership of Space-Faring Nations and Space User Groups, will provide a sufficiently complex Multi-Year, Multi-Mission Space Mission Planning Optimization Task, particularly with funds being so short, that a model such as is presented in this Paper could be of great use in optimizing future International Partnership SEAs.

9. 0 CONCLUSIONS

9.1) The BIP/ATLAS Constrained Optimization Combination can be applied to Optimizing Multi-

Year (35 yr.-45 yr.) SEA Space Mission Planning Tasks of ~ 200 Missions. Various Solvers exist that can optimize such alternative SEAs, including those involved with other Space-Faring Nations and with multiple User Groups.

9.2) In Optimizing 3 major SEAs of 30 yr.-45 yr. planning duration and ~200 missions, the ILOG CPLEX (8.0) was the most efficient Solver for Space Planning 'RUNS'.

9.3) More of the SEAs should store consumables at Gateways and should practice this procedure as part of the operating functions of the (RSSTI)[2]. There is a need to include the real-time inventorying of stored supplies at the "Gateways" and to include specific plans and methodologies in SEAs for use of these stored commodities by subsequent missions.

10.0 REFERENCES

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